UNITED STATES PATENT APPLICATION

of

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for

**IMAGING SYSTEM WITH A TWO-AXIS-GIMBAL
MIRROR SCAN SYSTEM APPARATUS AND METHOD**

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MIRROR SCAN SYSTEM APPARATUS AND METHOD

5   ## GOVERNMENT RIGHTS

BACKGROUND OF THE INVENTION

10   The present invention relates to an orbital optical imaging system, and in particular to a method and apparatus that controls a scanning mirror, which provides a reflected image to a multiband (i.e., multiple spectral bands) focal plane array.

Satellites are widely used as platforms for various atmospheric monitoring instruments. For example, the United States National Oceanic and Atmospheric Administration (NOAA)

15   operates a number of satellites that are used for weather monitoring. Some of these satellites operate in a geosynchronous orbit and regularly scan over predetermined areas of the Earth in order to monitor current weather conditions and provide data to weather forecasting systems.

The optical imaging instrument (an "imager") on these satellites includes several optical spectral bands that are used to monitor the weather. For example, there may be a visible

20   imaging band and several infrared imaging bands. These various spectral bands together provide information regarding cloud cover and various forms of precipitation (e.g., rain, snow, sleet or hail) over the area of the Earth being monitored.

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Technology improvements have recently made available large arrays comprising hundreds of optical detectors, that were not available when the current weather satellites were designed and manufactured. It is now possible to combine side-by-side, on a common surface, several long, line arrays of optical detectors, with each line array having detectors responsive to a particular spectral band. This assembly is often referred to as a multiband array of detectors. If this assembly of detectors is then installed on the focal plane of an optical instrument, the assembly is called a multiband focal plane array (MBFPA). For example, the MBFPA of a weather imager may include a visible band (e.g., 0.5 – 0.7 micrometers) and a number of infrared bands (e.g., eight bands over the range 1.8 – 13 micrometers).

An engineering obstacle to the use of a MBFPA in an advanced imager is the geometric distortion due to an optical effect known as "image rotation" that results if the MBFPA is used in combination with a conventional single-mirror scanning system. The purpose of the scanning system is to project a selected portion of the Earth (the "scene") onto the MBFPA. In a conventional, single-mirror scanning system the mirror is first positioned relative to a first axis (e.g., to select the elevation of the scan), and then scanned about a second axis (e.g., azimuth) while holding the mirror position constant with respect to the first axis. The first and second axes are orthogonal. This scan process allows a user to select the Earth scene (usually in an automated sequence of scans) to be viewed by the imaging instrument. The scanning process can be repeated in a progressive sequence to obtain a multi-spectral image of the full Earth disk.

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However, the use of a conventional, single-mirror scan system in combination with the MBFPA causes two undesirable errors. The first error is a pixel-to-pixel *registration* error within a frame, which is a geometrical distortion in which the pixels within an image frame are misaligned with respect to each other, such that they are not "observed" at their true positions in the Earth scene. The second error is a band-to-band *coregistration* error. The coregistration error is a geometrical effect in which the detectors in different spectral line arrays of the MBFPA do not traverse the same area of the Earth scene during the scan. Both of these errors have an adverse effect on the quality of weather imagery. Therefore, a technique is needed to image an Earth scene onto the MBFPA without introducing the registration and coregistration errors in order to utilize the new MBFPA technology effectively. Several techniques are currently under investigation.

One technique is to use an assemblage of multiple beamsplitters to split the incoming light flux onto a series of separate, single-band focal plane arrays of detectors. However, this technique does not enable the use of the MBFPA since the separate focal planes have detectors of only a single spectral imaging band. In addition, this technique does not correct for the pixel-to-pixel registration error. This design approach is also relatively costly and complex due to the precision required in the physical alignment and calibration of the assemblage of beamsplitters.

A second approach under consideration is to use two cascaded scanning mirrors. The first mirror would scan about a first axis (e.g., scan in elevation), while the second mirror would scan about a second axis (e.g., scan in azimuth). This approach would correct both

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registration and coregistration errors and, indeed, enable the use of the MBFPA technology. However, since the mirror is a heavy component of the imager, adding an additional mirror is undesirable because it adds to the mass and bulk of the satellite. Significantly, it adds to the launch mass of the satellite.

5   Therefore, there is a need for an imaging system comprising a MBFPA that is free from the undesirable geometrical errors of image registration and coregistration.

SUMMARY OF THE INVENTION

Briefly, according to the present invention, a mirror is scanned to provide an image of

10   a desired portion of the Earth to a multiband focal plane array (MBFPA). The mirror is first positioned relative to a first axis (e.g., elevation) as a starting position of the image scan. The mirror is then scanned about a second axis and repositioned relative to the first axis while scanning the mirror about the second axis (e.g. azimuth).

This invention may be used in a satellite-based weather imaging instrument to remove

15   registration and coregistration errors that occur when a conventional, single-mirror scan system is used in combination with the MBFPA. The present invention positions the mirror relative to the first axis (e.g., the elevation at the start of the scan), and while scanning the mirror about the second axis (e.g., azimuth), the mirror is repositioned in a controlled manner relative to the first axis. That is, the invention dynamically adjusts the position of the mirror relative to the

20   first axis while scanning about the second axis. Scanning about the first axis may be an elevation scan while scanning about the second axis may be an azimuth scan, or vis-a-versa.

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Advantageously, this control technique ensures that the images within each spectral band are spatially registered pixel-by-pixel within the image frame, and that the images of the various spectral bands are spatially coregistered with respect to each other. The present invention provides a scan-control technique for a single-mirror scan system that enables the use

5   of the MBFPA in an imaging instrument.

These and other objects, features and advantages of the present invention will become apparent in light of the following detailed description of preferred embodiments thereof, as illustrated in the accompanying drawings.

10   **BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a pictorial illustration of a satellite-based imaging system positioned over the Earth;

FIG. 2 is a pictorial illustration presenting the image rotation in terms of the "equivalent" rotation of a line vector;

15   FIG. 3 illustrates a contour plot of θ as a function of azimuth angle A and elevation angle E;

FIG. 4 illustrates the effect of "image rotation" on pixel-to-pixel registration error within a frame;

FIG. 5 illustrates the geometry of the MBFPA showing an effective "rotation" due to

20   the scanning of the mirror (FIG. 1) that provides an image to the MBFPA;

FIG. 6 is an illustration of how scanning the mirror (FIG. 1) in azimuth across the

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Earth disk while holding the elevation of the mirror constant, causes the detectors of the various bands of the MBFPA to pass through a given geodetic longitude L_G;

FIG. 7 is a plot of the mirror elevation position versus azimuth position illustrating the taper in elevation as a function of azimuth; and

FIG. 8 illustrates a flow chart illustration of a mirror control routine.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 is a pictorial illustration of a satellite-based imaging system 10 positioned over the Earth 12. The imaging system 10 includes a mirror 14 having a reflective surface 15 that provides a reflected image of an area of the Earth onto a multiband focal plane array (MBFPA) 16. The MBFPA 16 includes a plurality of distinct optical imaging spectral bands 18-21 that each includes a plurality of detectors. The first band 18 may be a visible imaging band while the other bands 19-21 are infrared bands each operating at a slightly different wavelength (e.g., in the range of about 1.8 - 13 micrometers). The imaging system 10 may be used in a weather satellite.

The mirror 14 rotates in a limited range about a first axis 22 and limited range about a second axis 23, in order to provide a reflected image of a selected area of the Earth. Rotation about the first axis 22 scans the mirror 14 in elevation, while rotation of the mirror about the second axis 23 provides the ability to scan the mirror 14 in azimuth. The system 10 also includes a scan controller 24 that provides signals on lines 25, 26 to actuators 27, 28 that position the mirror about the first and second axes 22, 23, respectively. The system 10 may

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use an open or closed loop control system architecture to position and scan the mirror 14. We shall now briefly describe the optical effect known as "image rotation" that is a source of registration and coregistration errors.

FIG. 2 is a pictorial illustration 30 presenting the image rotation analytically modeled in terms of the "equivalent" rotation of a line vector, $\overline{L}$ 32, in the MBFPA as projected onto a flat Earth. Alternatively, one of ordinary skill will recognize that it is also possible to model the image rotation as the projection of the Earth scene on the focal plane and to extend the analysis to the geometry of a spherical Earth. For the modeling we use the *method of images* to replace the line vector $\overline{L}$ 32 with its image vector, $\overline{I}$ 34 (this technique is often used to solve electrostatics problems which are analytically analogous). This technique allows us to use the image vector $\overline{I}$ 34 to calculate the line vector's projection onto the Earth, as though the image vector $\overline{I}$ 34 were in free space, thus removing the complication of the mirror's presence. In the calculation, an important parameter is the mirror's normal, $\hat{n}$ 36. We can express the image vector $\overline{I}$ 34 in terms of the normal $\hat{n}$ 36 and use the normal $\hat{n}$ to keep track of the mirror's 14 orientation during the scanning process. In the scan process, the normal $\hat{n}$ 36 becomes a function of the North-South elevation, E, and the East-West azimuth, A. We shall now discuss an elevation rotation of the mirror 14 (i.e., a N-S scan).

First consider the image rotation in the case of an elevation scan (i.e., a N-S scan) in which azimuth $A = 0$ while elevation E varies. Referring to FIG. 2, we can express the image as $\overline{I} = I_n \hat{n} + I_p \hat{p}$ where $I_n = -\hat{n} \cdot \overline{L}$ and $I_p = \hat{p} \cdot \overline{L}$. At $E = 0$ (nadir), the normal is $\hat{n}_0 = \dfrac{-\hat{y} + \hat{z}}{\sqrt{2}}$.

For a N-S scan, through an angle E about the $\hat{z}$-axis, $\hat{n} = \dfrac{-\sin E\hat{x} - \cos E\hat{y} + 1\hat{z}}{\sqrt{2}}$. The

companion unit vector, $\hat{p}$ 38, is given by $\hat{p} = \dfrac{(\hat{n} \times \overline{L}) \times \hat{n}}{|(\hat{n} \times \overline{L}) \times \hat{n}|}$. From the above relationships, after

some manipulation, the image vector $\overline{I}$ can be expressed as:

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$$\overline{I} = L(-\sin E \cos E\hat{x} + \sin^2 E\hat{y} + \cos E\hat{z}). \qquad \text{(EQ. 1)}$$

The rotation angle of the line vector $\overline{L}$ is given by:

$$\theta = \tan^{-1}\left(\frac{\hat{x} \cdot \overline{I}}{\hat{z} \cdot \overline{I}}\right) \qquad \text{(EQ. 2)}$$

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Using the expression for $\overline{I}$ in EQ. 1, EQ. 2 can be rewritten as:

$$\theta = -\tan^{-1}[\sin E] \qquad \text{(EQ. 3)}$$

15   At this point in the analysis the scan is limited to a scan in E only. At the small values E,

$\theta \approx -E$, which is the case at geostationary orbit where approximately $E \le 8°$.

The extension of the analysis to scan in both elevation E and azimuth A proceeds in a

similar manner. After some mathematics, we obtain the following expression for the rotation

angle θ:

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$$\theta = \tan^{-1}\left[\sin E \tan(A - \tfrac{\pi}{4})\right] \qquad\qquad \text{(EQ. 4)}$$

FIG. 3 illustrates a contour plot 40 of θ as a function of A and E, as calculated from EQ. 4.

5 The azimuth angle A is plotted along a horizontal axis 41 and elevation angle E is plotted along

a vertical axis 42. Note that, to very close approximations, the scan mirror's azimuth encoder

angle, A, is one-half of the pointing angle in the azimuth direction while the elevation encoder

angle E is equal to the pointing angle in the elevation direction, such that, a range of rotation

of approximately $(-4° \le A \le 4°)$ and $(-8° \le E \le 8°)$ provides full coverage of the Earth disk, as

10 viewed from geostationary orbit. We now have the mathematical tools in place to calculate the

registration and coregistration errors caused by image rotation.

First, we calculate the registration error. FIG. 4 illustrates the effect of image rotation

on pixel-to-pixel registration within an image frame. In the interest of simplicity, only three

points (A,B,C) 43-45 on the Earth and three detectors 46-48 in a line array 49 (of a particular

15 spectral band) that "correspond" to observation of these points are illustrated. The points

(A,B,C) 43-45 are the "true" locations of these points in the scene, and the corresponding

detectors 46-48 are the "observed" locations of the points. If the three points (A,B,C) 43-45

lay in the centers of their corresponding detectors 46-48, the pixels are registered; if not, there

is a registration error.

20 Referring still to FIG. 4, in scan #1 49 50 at the Equator ($E_1 = 0$), there is zero image

rotation, and the points (A,B,C) 43-45 are aligned with their corresponding detectors 46-48.

That is, there is no registration error because the "true" and "observed" locations of the points coalesce.

In contrast, in scan #2 55 at a location above the Equator ($E_2 > 0$), the image rotation displaces the location of the points (A, C) 43, 45 from their corresponding detectors 46, 48, respectively. This effect causes a registration error, as shown in the ~~"blow-up" of~~ FIG. 4 B. The amount of registration error increases with elevation (i.e., at more northerly scans), where the image rotation increases in magnitude.

The registration error is given mathematically by:

$$\text{Error} = L/2 \sin \theta \qquad \text{(EQ. 5)}$$

In EQ. 5, the quantity L is the scan swath width, which is the projection of a N-S line array onto the Earth, and θ is the image rotation angle.

As a numerical example, assume an array length of 1/2", for which L = 568 km. At an elevation of E = 4° (i.e., an Earth scene centered at a geodetic latitude of approximately 23.6°) along the geodetic longitude that passes through the satellite's nadir point, we calculate from EQ. 5 a registration error of approximately 20 km. Extending this result (for a single swath) to a 2000-km by 2000-km image gives a registration error of approximately 40 km at E = 4°, which exceeds typical requirements in weather imaging.

Next, we consider the band-to-band coregistration error. FIG. 5 illustrates the geometry of the "rotation" of the MBFPA 16 due to the orientation of the scanning mirror 14

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(FIG. 1), that provides an image of the Earth scene to the MBFPA. One of ordinary skill will recognize that the effective "rotation" of the MBFPA is a modeling construct of the analysis. The MBFPA does not actually rotate; rather, it is the scan mirror's reflection of the Earth scene onto the MBFPA that rotates while the MBFPA remains stationary. The line arrays of the optical imaging bands of the MBFPA 16 nominally extend in the N-S direction in the absence of image rotation, as in the azimuth scan centered on the Equator. Scanning the mirror in elevation at geodetic latitudes above the Equator causes the projection of the Earth scene on the MBFPA to rotate through angle θ 51, which can be modeled as an "effective" rotation of the MBFPA, as depicted in FIG. 5.

In FIG. 5 we see that the effective rotation of the MBPFA 16 causes a *coregistration* error to occur between corresponding detectors 52-54 of the various spectral bands 18-21, respectively. "Corresponding" detectors refers to detectors of different spectral bands that would trace the same geodetic latitude in the absence of image rotation. For example, a set of "corresponding" detectors are the detectors 52-54. The coregistration error between the corresponding detectors of two different spectral bands, spatially separated in the MBFPA by the distance, D, is given by the following expression:

$$Error = \frac{D}{\Delta}\sin\theta \times 100\% \qquad \text{(EQ. 6)}$$

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where Δ is the dimension of the square detector. In EQ. 6, the coregistration error is normalized by Δ. Referring still to FIG. 5, the largest coregistration error occurs between the spectral bands that are the farthest apart in the MBFPA (i.e., bands 18 and 21). In this case, $D = W - \Delta$, where W is equal to the width of the MBFPA. As an example, if $\Delta = 45$ μm and

5 $W = 14.7$ mm, then the coregistration error between bands 18 and 21 is approximately 2300% at an elevation of $E = 4°$ (a point at a geodetic latitude of approximately 23.6°). This coregistration error grossly exceeds the error limits of a weather imaging system of acceptable image quality and indicates the need for the present invention. We shall now describe how the present invention eliminates the band-to-band coregistration error.

10 Referring to FIG. 6, scanning the mirror 14 (FIG. 1) in azimuth 60 across the Earth disk while holding the elevation of the mirror constant, causes the detectors of the various bands 18-21 of the MBFPA to pass through a given geodetic longitude L_G 62 at a different geodetic latitude. For example, during the azimuth scan the detector 52 *D-1* passes through L_G 62 at a slightly higher geodetic latitude than when the detector 56 *D-N* passed through L_G 62

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15 and, in fact, this effect is the source of the band-to-band coregistration error. The consequence of the error is that the corresponding detectors of various spectral bands do not traverse the same point ("spot") in an Earth scene during the scan. According to the present invention, during each scan the elevation of the scanning mirror 14 (FIG. 1) is also controlled as a function of the scan position in elevation and azimuth, such that when the detector 52 *D-1*

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20 reaches L_G 62, it is at the same geodetic latitude at which the detector 56 *D-N* passed through L_G. Tapering the elevation of the scan versus position of the scan mirror in this way removes

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the coregistration error by ensuring that the detectors of each spectral band in the MBFPA

sample their data at identical geodetic sample points in the Earth scene. Accordingly, the scan

process of this invention removes the effect of image rotation and brings the various spectral

bands of the MBFPA into coregistration. We shall now quantitatively discuss the present

5   invention.

Since $dE/dA = \tan\theta$, the required elevation taper as a function of scan position (the

azimuth A and elevation E_W) is given by:

$$E = E_W + \int_{A_W}^{A} \tan\theta \, dA \qquad \text{(EQ. 7)}$$

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where E_W and A_W are the discrete elevation and azimuth settings, respectively, at the

beginning of the scan. From EQ. 4 we see that the integrand in EQ. 7 can be expressed as:

$$\tan\theta = \sin E \tan(A - \frac{\pi}{4}). \qquad \text{(EQ. 8)}$$

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Substitution of (EQ. 8) into (EQ. 7) yields:

$$E = E_W + \sin E \int_{A_W}^{A} \tan(A - \frac{\pi}{4}) \, dA . \qquad \text{(EQ. 9)}$$

Evaluating the integral in EQ. 9 we obtain:

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$$E = E_W - \sin E \ln\left[\frac{\cos(A - \frac{\pi}{4})}{\cos(A_W - \frac{\pi}{4})}\right] \qquad \text{(EQ. 10)}$$

We see that the right most term of EQ. 10 is the mirror elevation taper versus azimuth that is

5   required to prevent/reduce coregistration errors. We can solve EQ. 10 for E by either

numerical iteration or a technique using a Taylor series expansion of $\sin E$. The latter

technique works best if we first rearrange EQ. 10 to exploit the rapid convergence of a Taylor

series if cast in terms of a variable whose magnitude is small. Accordingly, we introduce the

variable $x = E - E_W$ and rewrite EQ. 10 as:

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$$x = \sin(x + E_W)f_A \qquad \text{(EQ. 11)}$$

where for convenience we define $f_A = -\ln\left[\frac{\cos(A - \frac{\pi}{4})}{\cos(A_W - \frac{\pi}{4})}\right]$. We can use a trigonometric

identity to rewrite EQ. 11 as:

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$$x = (\cos E_W \sin x + \sin E_W \cos x)f_A \qquad \text{(EQ. 12)}$$

Expanding the terms of EQ. 12 involving x as a Taylor series yields:

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$$x = [\cos E_W (x - x^3/3! + \cdots) + \sin E_W (1 - x^2/2! + \cdots)] f_A \qquad \text{(EQ. 13)}$$

The convergence is rapid because $|x| \ll 1$. Accordingly, we omit terms in x higher than

second order to obtain the quadratic equation:

$$x^2 + bx + c = 0 \qquad \text{(EQ. 14)}$$

where

$$b = 2 \frac{1 - f_A \cos E_W}{f_A \sin E_W} \qquad \text{(EQ. 15a)}$$

$$c = -2 \qquad \text{(EQ. 15b)}$$

From the definition of x we obtain:

$$E = E_W + x_p \qquad \text{(EQ. 16)}$$

where x_p, the elevation taper, is given by the appropriate root of EQ. 14. It should be noted

that we have also solved EQ. 13 by keeping the third-order terms in x and found negligible

change in the results. Alternative solutions based on numerical iteration can be used to solve

EQ. 10 for E to arbitrary accuracy.

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FIG. 7 is a plot 70 of mirror elevation position versus azimuth encoder position based

upon EQ. 16, illustrating the taper in elevation as a function of azimuth ~~(the "jaggies" evident~~

~~in the curves are not real but rather an artifact of the software/printer used to generate the~~

~~plot).~~ Azimuth encoder angle A is plotted along a horizontal axis 72 and elevation angle E is

5   plotted along a vertical axis 74. We shall now briefly describe the operational control of the

mirror 14 (FIG. 1).

FIG. 8 is a flow chart illustration of a mirror control routine 80. The routine 80 can be

performed as a series of programmable software steps executed by the control logic of the scan

controller 24 (FIG. 1). Referring to FIGs. 1, 7 and 8, a first step 82 in the routine 80 is to

10   position the mirror 14 (e.g., in a discrete step which depends on the swath width of the line

arrays in the MBFPA) with respect to the first axis 22 (FIG. 1). This position is based upon

the location in elevation of the desired Earth scene to be imaged in the scanning process. The

scan controller 24 determines the elevation angle at which the mirror 14 must be placed

relative to the first axis 22 to image the desired Earth scene, and provides a command signal

15   on the line 25 to position the mirror accordingly. As an example, this initial elevation position

is shown in FIG. 7 as starting point 84. Once the mirror 14 is in the desired elevation position

relative to the first axis 22, step 86 is then executed to scan the mirror about the second axis 23

in azimuth. According to the present invention, step 88 is then executed to adjust the position

of the mirror in a prescribed way relative to the first axis 22 as the mirror continues to scan

20   about the second axis 23. That is, referring to FIG. 7, as the mirror begins to scan in azimuth

from the starting point 84, the scan controller 24 (FIG. 1) commands the mirror to follow line

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90. Significantly, as the mirror scans in azimuth, the scan controller also commands the elevation actuator 28 so the mirror position tracks the prescribed elevation "taper" along line 90. At the end of the azimuth scan, the mirror will be at end position 92. The scan controller then commands the mirror to position 94 and begins scanning from right-to-left along line 96.

5   Controlling the mirror position with respect to the first axis 22 as the mirror rotatably scans about the second axis 23 ideally eliminates both the registration and coregistration errors. This is an example of the scan process. The actual size of the scan steps in elevation (one degree in this example) will depend on the length of the line arrays of the MBFPA used in the instrument.

10   The elevation taper of the present invention causes the swaths of successive scans to overlap in coverage slightly, which varies gradually in amount over the course of the azimuth scan. Simple data editing to remove or average out redundant pixels in the overlapped regions corrects this effect. Editing options include disregarding the "old" pixels of the previous scan in favor of the "new" pixels of the present scan (or vice versa), or averaging or weighting the

15   "new" and "old" overlapped pixels. Although the present invention has been primarily discussed in the context of initially setting the position of the mirror with respect to elevation, and then scanning in azimuth while elevation is changed as a function of scan position, one of ordinary skill in the art will recognize that the roles of the two axes can be reversed. For example, the scan may occur in elevation and the azimuth position is controlled as a function

20   of scan mirror's position.

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Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

5   What is claimed is:

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